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ABSTRACT

This paper discusses nondestructive testing (NDT) methods and techniques for detection of material and manufacturing anomalies in state-of-the-art graphite composites. Introduction of composites into large-scale production depends in large measure on the successful application of NDT for process control and monitoring. Visual, liquid-penetrant, radiographic, ultrasonic, sonic, thermal, and acoustic-emission NDT methods are used to evaluate graphite fiber composite aircraft specimens and structures. Reference standards are fabricated with built-in discontinuities, commensurate with each structural article fabricated. The test specimens and parts were tested by various methods in order to determine optimum discontinuity detection. Tests were conducted on research and development graphite composite aircraft structures consisting of (1) molded graphite flap ribs, (2) graphite composite flap assembly, and (3) graphite composite horizontal stabilizer assembly.

INTRODUCTION

The Douglas Aircraft Co., McDonnell Douglas Corp., has developed a comprehensive background in advanced composite technology through numerous contracted and independently funded research programs. These programs consisted of fabricating various aircraft structures from glass-fiber, boron-fiber, and graphite-fiber composites. In this paper, discussion is confined to graphite-epoxy composites and the NDT methods used to evaluate them.

The graphite composite programs consist of the following: (1) graphite flap, (2) molded graphite flap rib, and (3) graphite composite horizontal stabilizer. The graphite flap and molded flap rib programs have been completed under Douglas independent research and development (IRAD). The graphite composite horizontal stabilizer program is presently under development.

The method of fabrication and materials used for each program varied. Hence, the results and selection of the NDT methods were also slightly different. Therefore, each program will be discussed separately to avoid confusion.

NDT IN THE PRODUCT CYCLE

In the composite programs, NDT is used for in-process quality control of materials, subassembly, and final assembly. The application of NDT methods throughout the product cycle provides the development engineer with control over the various processes and quality assurance of the finished product. Receiving inspections are used to evaluate in-coming materials and discrepancies are reported to the supplier. At Douglas, only optimum quality material has been selected for fabrication of the assembly. During the fabrication cycle, typical product specimens are made and tested. Defective specimens are carefully evaluated to determine the changes in the process necessary to produce acceptable quality parts. When the process is controlled, actual product subassemblies are fabricated and tested. Defective subassemblies are either repaired or discarded. The subassemblies are joined and the finished product is tested. Throughout the fabrication cycle, NDT results are presented by permanent recording methods, i.e., photographs, ultrasonic facsimile recordings, or X-ray radiographs. This provides the development engineer with data he can readily understand and use to best advantage.

NDT method selection is generally based on part geometry and composition, defect size, location, orientation, and availability of test equipment. Very often, more than one NDT method is used because different conditions or defects are revealed, as shown in Figure 1. Typical specimens and parts were evaluated with the use of visual, liquid penetrant, radiographic, ultrasonic, and sonic methods. Limited investigations using thermal and acoustic-emission methods were conducted.

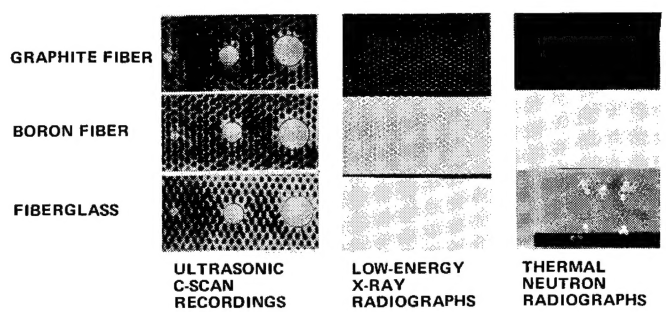


FIGURE 1. CORRELATION OF RESULTS FOR VARIOUS TEST METHODS ON COMPOSITE HONEYCOMB SPECIMENS

Ultrasonic testing may be performed by two basic methods: through-transmission or pulse-echo. The energy passing completely through the part is recorded by the through-transmission technique. The energy reflected from a discontinuity, or its related effect to the total response, is recorded by the pulse-echo technique. The through-transmission technique has the advantage of not being greatly affected by surface contour, surface roughness, or part alignment, and only one signal is received for processing the total pass-through energy. In contrast, the pulse-echo method is drastically affected by the same factors, since in this method the sound passes through the part twice, resulting in higher attenuation and sound scatter degradation. The two techniques are schematically shown in Figure 2. The

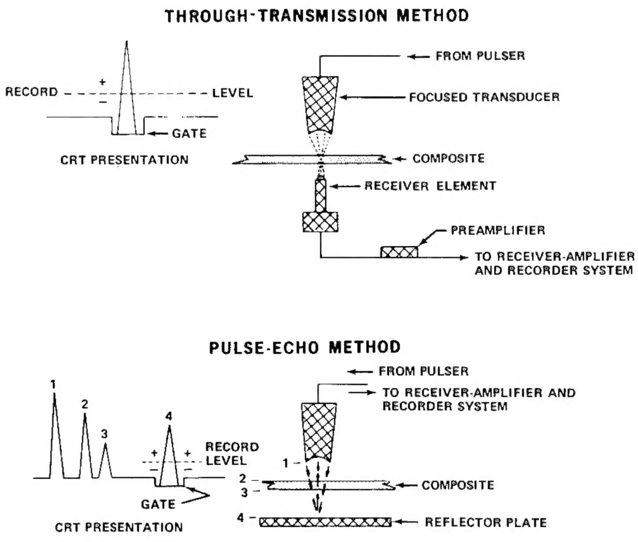


FIGURE 2. ULTRASONIC INSPECTION TECHNIQUES

pulse-echo technique was used to obtain the test results illustrated in this report.

Radiographic examinations were conducted with the use of a Picker 5 to 50-kv X-ray machine with a 0.5-mm-diameter focal spot and beryllium-window tube. The X-ray film used is fine grain, single or double emulsion. It is exposed for various lengths of time in direct proportion to the thickness of the material being evaluated. The processed negative-image radiograph is taken to the photo lab for reproduction. The film is placed on a light-box and high-contrast print paper is placed over the film, exposed, and processed. This method results in a positive-image reproduction, i.e., light areas are less dense and dark areas are more dense.

A-4 GRAPHITE COMPOSITE HORIZONTAL STABILIZER

Douglas is presently developing a flightworthy horizontal stabilizer structure for the A-4 aircraft, using graphite filament/ epoxy resin composite as the primary structural material. The horizontal stabilizer, shown in Figure 3, was selected because of its primary structural significance, its relative compactness, and its potential for significant weight reduction. The structural configuration proposed for the stabilizer is eminently suitable for large, heavily loaded, wing-type structures. The presence of contour breaks across the center section is typical of many types of wings and introduces the problems associated with compound curvature and taper into the fabrication of the skins. In addition, the mounting provisions for the graphite composite stabilizer are common to the existing metal component, which will facilitate flight test. The graphite composite stabilizer is expected to weigh 34 percent less than the existing metal component.

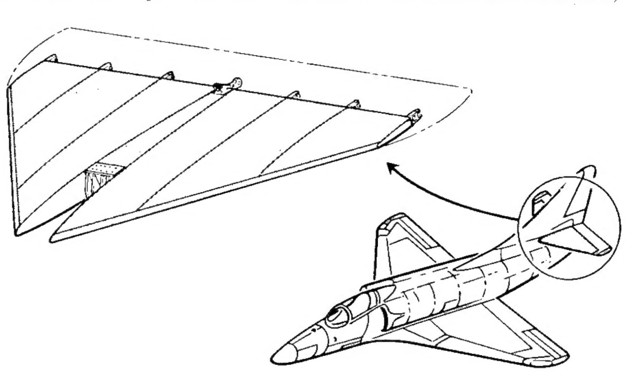


FIGURE 3. STRUCTURAL ARRANGEMENT OF HORIZONTAL STABILIZER

Graphite has been selected as the basic filamentary material mainly because of its superior combination of specific strength and stiffness. The selected material combination, Narmco 5206 graphite prepreg (Modmor II fiber), has demonstrated a superiority over other candidate graphite materials. A multispar design, Figure 4, with thick solid graphite skins has been selected on the basis of cost and weight, and a combination of other desirable properties.

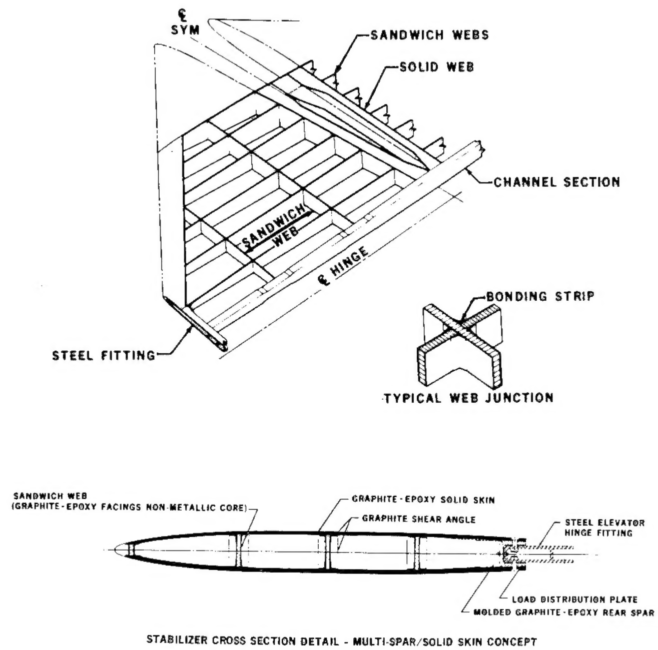


FIGURE 4. INTERNAL STRUCTURAL ASSEMBLY OF HORIZONTAL STABILIZER

MATERIAL TESTING AND QUALIFICATION

Structural design studies are being accompanied by a program of material testing and qualification which will:

1. Define optimum processing conditions for the selected constituent materials.

2. Provide information for the evaluation of material design allowables.

Throughout the test programs, specimens are evaluated by visual and NDT methods for voids, cracks, lack of bond, delaminations, etc. Early in the program, the specimens were radiographed and ultrasonically tested. It soon became apparent that the ultrasonic C-scan recordings provided better information concerning laminate quality than did radiography. Hence, most of the

specimens were evaluated by ultrasonic methods. Figure 5 illustrates the results obtained by low-energy X-ray (25v) and ultrasonic (10 MHz) methods for a 0.090-inch thick graphite-epoxy fatigue specimen. The radiograph shows fiber orientation (light areas) at 0, 90, and ±45 degrees. Ultrasonic method indicates the area to be porous.

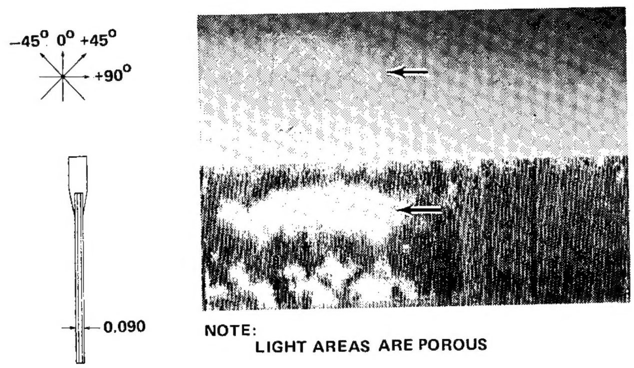


FIGURE 5. RADIOGRAPHIC POSITIVE PRINT AND ULTRASONIC C-SCAN RECORDING OF GRAPHITE COMPOSITE FATIGUE SPECIMEN

Figure 6 illustrates the results obtained from a 0.085-inch, ±45-degree laminate fatigue specimen by X-ray and ultrasonic methods. The ultrasonic results obtained at equal signal gain but at two different frequencies show a variation in transmission. The lower frequency 2.25-MHz wave penetrates more readily than does the 10-MHz wave and hence the specimen appears less porous at lower frequencies. The technique of variable frequency provides a means of locating more severe discontinuities at low frequency and then checking the specimen again at a higher frequency to locate less severe conditions or variations. Similar results may be obtained at a fixed frequency by varying the signal height for alternate scans as illustrated in Figure 7. Note the change in results obtained from the void at location A.

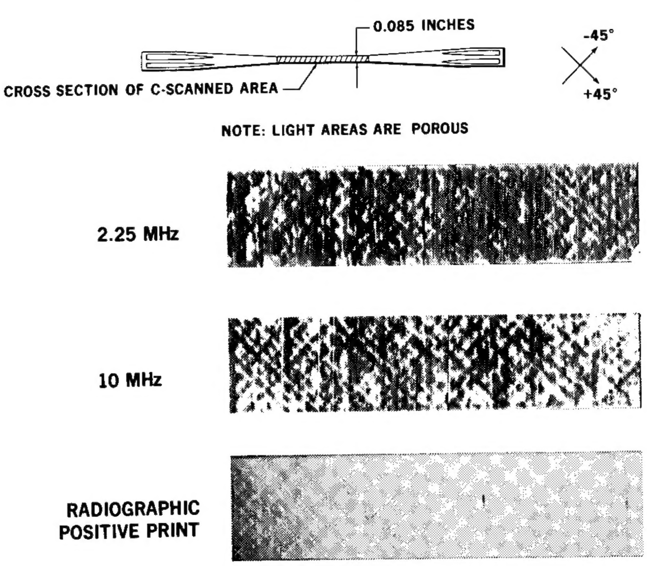


FIGURE 6. ULTRASONIC C-SCAN AND X-RAY POSITIVE PRINT OF GRAPHITE COMPOSITE FATIGUE SPECIMEN

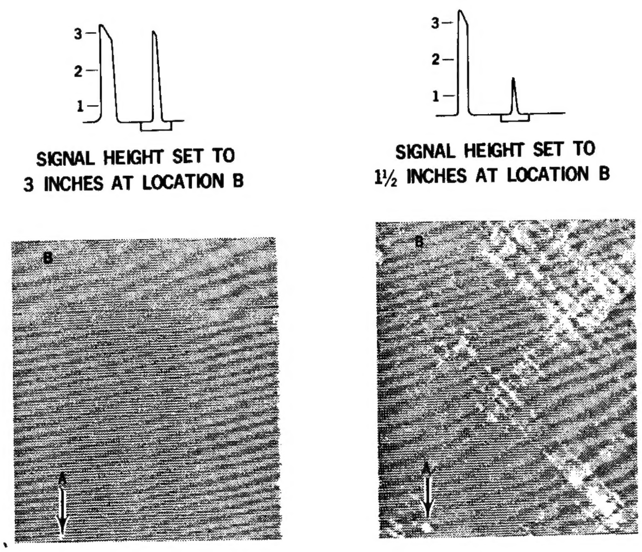


FIGURE 7. ULTRASONIC C-SCANS OF GRAPHITE COMPOSITE AT TWO SIGNAL LEVELS

The results obtained from five graphite composite laminate IITRI tensile specimens, 4 ply and 0.025-inch thick with unidirectional fiber orientation, are shown in Figure 8. In this particular case, visual cracks parallel to the unidirectional fiber orientation were evident. The true nature of the cracks was difficult to determine radiographically but was clearly evident by ultrasonic C-scan.

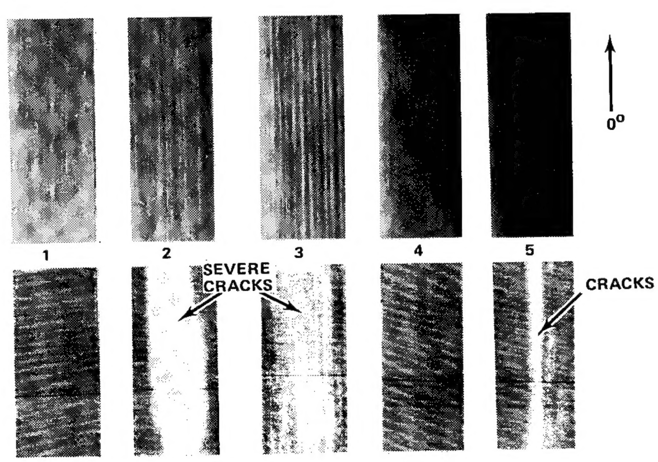


FIGURE 8. ULTRASONIC C-SCANS AND RADIOGRAPHIC POSITIVE PRINTS OF GRAPHITE COMPOSITE TENSILE SPECIMENS

Although only defective conditions are illustrated in Figures 5 through 8, acceptable quality specimens were produced once optimum processing parameters were determined. Infrequently, a discontinuity typical to that shown in Figure 9 is detected. Just what causes this kind of discontinuity has not been determined. It is not a large void as indicated by the good ultrasonic transmission in the center. Process engineers have determined that it is not a precleaning defect. It may be an entrapment of air or solvent gas just prior to gel of the resin system.

The I-beam and box-beam test specimens shown in Figure 10 have been fabricated. The Morganite skins are nondestructively tested prior to bonding to the Hexel HRP 1/4-inch, 3.5-density honeycomb. After bonding with Narmco Metlbond 329, the honeycomb is visually checked and tap tested prior to NDT evaluation. The panels are X-rayed for inclusions, filleting, and crushed core evaluation. The panels are then ultrasonically checked for bond quality on both sides of the panel.

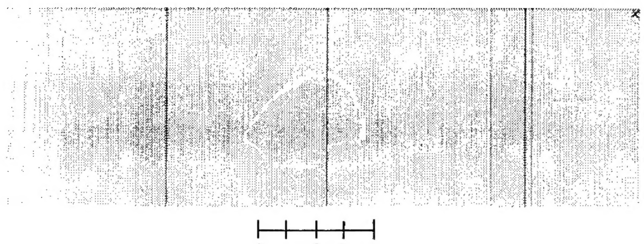


FIGURE 9. ULTRASONIC C-SCAN OF GRAPHITE COMPOSITE LAMINATE SHOWING UNDEFINED DISCONTINUITY

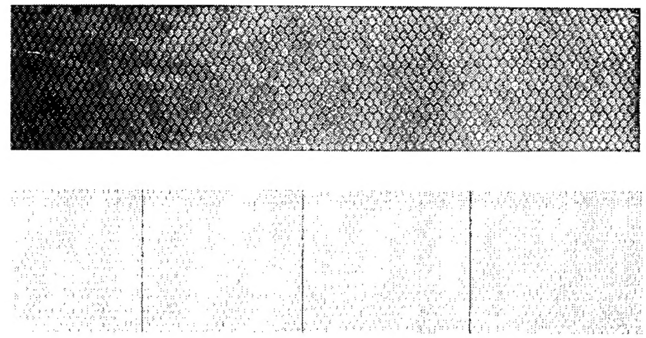
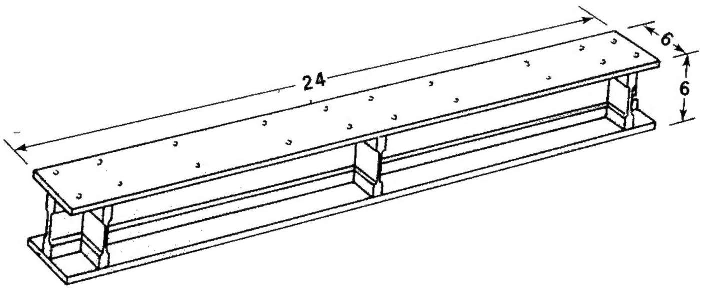
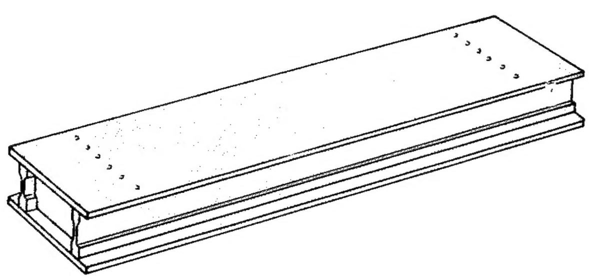


FIGURE 11. GRAPHITE COMPOSITE/PHENOLIC HONEYCOMB CORE I-BEAM WEB ASSEMBLY



I-BEAM TEST SPECIMEN



BOX-BEAM TEST SPECIMEN

FIGURE 10. GRAPHITE COMPOSITE STATIC LOAD AND FATIGUE TEST SPECIMENS

Ultrasonic C-scan testing of the honeycomb panels is difficult. The panels have a strong flotation force and must be held immersed by edge fixtures. A water squirter or bubbler used in conjunction with the search unit would eliminate the need to immerse the panels. The through-transmission technique eliminates the need for testing both face panels separately, which is presently required for pulse-echo testing. A through-transmission yoke assembly has been ordered. The ultrasonic results shown in Figure 11 were made by a pulse-echo, gated-back reflection technique with the use of a 10-MHz, shot-focus search unit. It is felt that better resolution would be obtained by employing higher frequencies with the pulse-echo techniques. A 15- and 25-MHz pulser-receiver module has been ordered for use with current instrumentation.

The honeycomb panels are joined together by L-shaped graphite-epoxy shear angles (Figure 2) in the I-beam, box-beam, and horizontal stabilizer. Present evaluations indicate that ultrasonic testing will not detect lack of bonding when standard instrumentation is used. Test specimens, representing the shear angle to honeycomb bond, have been obtained and will be evaluated with the use of the high-resolution ultrasonic Erdman Nanoscope or the Fokker Bond tester.

Test results on typical graphite composite/metal-bonded specimens indicate that the Shurtronics (eddy-sonic) Harmonic Bond tester can be used to evaluate metal to nonmetal bond joints. A Harmonic Bond tester has been ordered for this purpose.

The graphite-epoxy rear spar and solid skins (Figure 2) will be evaluated by X-ray and ultrasonic testing methods. The bonds between the metal load distributing plate to the rear spar and face sheets will be tested by ultrasonic or eddy-sonic methods.

A-4 GRAPHITE COMPOSITE FLAP ASSEMBLY

The A-4 flap assembly shown in Figure 12 was fabricated from Morganite II skins bonded to 5052 alloy honeycomb core by Narmco Metlbond 252. An added feature of the assembly was the successful fabrication of a molded graphite/epoxy actuator rib which is subsequently discussed.

Procedures for bonding the 4-ply flap skins were investigated. Figure 13, View A, illustrates that the initial material cured by standard procedures and making use of metal plates resulted in a porous laminate. A better quality laminate was obtained using silicone pressure pads. However, consultation with the supplier and initiative on his part resulted in much smoother raw material sheets. The results of these changes produced laminates of high quality as indicated in View B of Figure 13, when the laminates were cured between metal plates. The final flap skin was produced as a large V-shaped cover panel on a solid aluminum V-mold and thin aluminum top pressure plate. The upper and lower surfaces were radiographed and found to be of high quality except for one small area at the outer leading edge which was of greater thickness. A 2- by 6-inch area showed a porous condition typical of that illustrated in Figure 13, View A. The skin was not ultrasonically inspected because it was too long to fit inside the

FIGURE 12. A-4 AIRCRAFT, GRAPHITE COMPOSITE/ALUMINUM HONEYCOMB FLAP ASSEMBLY

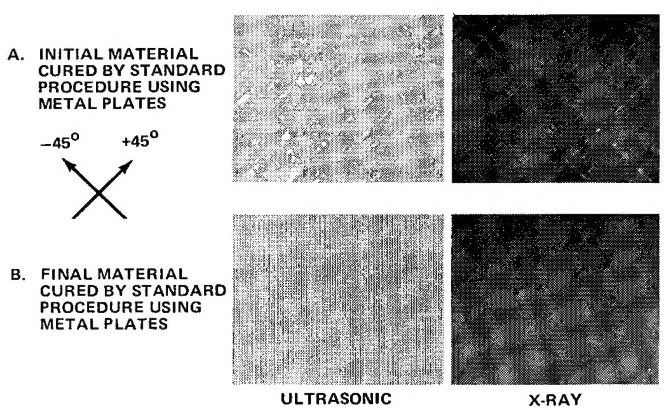


FIGURE 13. GRAPHITE-EPOXY FLAP SKINS (4 PLY, 0.024 IN. THICK)

ultrasonic C-scan immersion tank. The graphite skin to aluminum-core honeycomb bond was manually evaluated by tap test, 5-MHz contact ultrasonic test, and by the eddy-sonic Harmonic Bond tester.

The assembly was radiographed at 25 kv. The overall quality was good. Figure 14 shows the aft, outboard edge of the flap including the molded graphite rib. Slight wrinkles in the aluminum honeycomb are evident along the outer edge. The

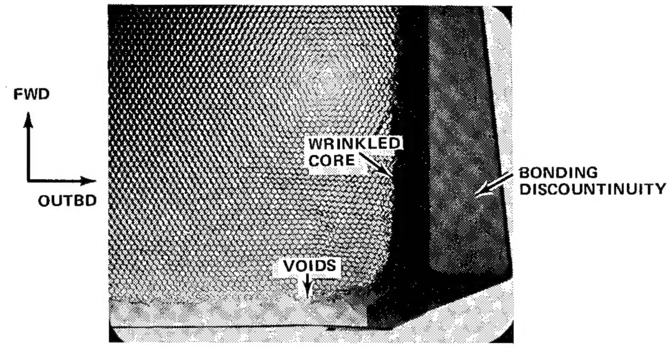


FIGURE 14. RADIOGRAPHIC POSITIVE PRINT OF GRAPHITE COMPOSITE/ALUMINUM HONEYCOMB FLAP ASSEMBLY

irregular trailing edge is located at the apex of the V-shaped honeycomb panel. This particular discontinuity is generated during machining of the honeycomb panel prior to bonding. Small voids are also evident in the adhesive located along the apex of the "V" at the trailing edge. The above discontinuities located at the trailing edge have no effect on the structural integrity of the flap.

MOLDED GRAPHITE FLAP RIB

A high-performance molding, for use as a concentrated load fitting (rib) in the A-4 graphite flap, was made as a subtask of the overall graphite flap program.

The Monsanto Company of Durham, North Carolina, under the direction of Douglas Aircraft Company, manufactured four molded graphite-epoxy ribs, shown in Figure 15. The four ribs (No. 0 through 3) were fabricated with BP-907 Resin/Thornel 50

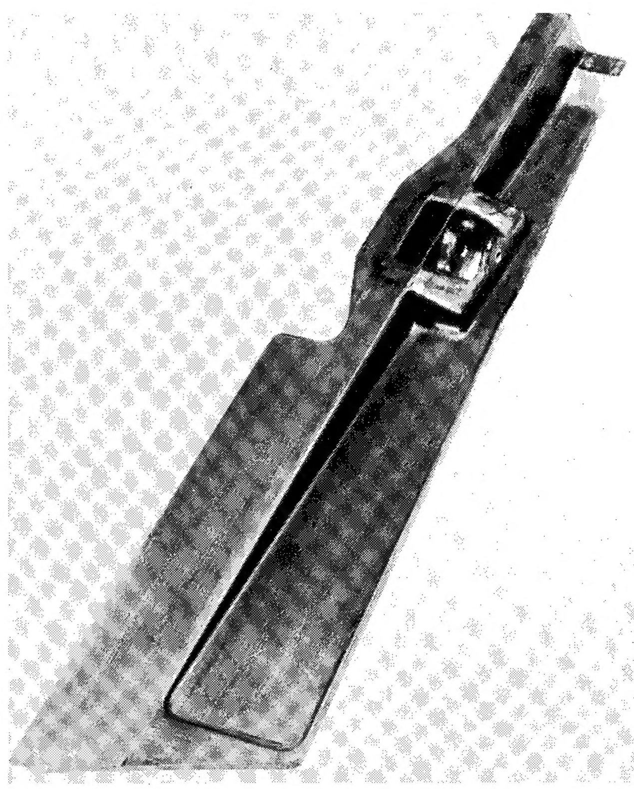


FIGURE 15. MOLDED GRAPHITE-EPOXY FLAP RIB

by Monsanto. The ribs were evaluated and compared on the basis of the physical properties obtained from their quality control (QC) tabs and from nondestructive examination performed on each. Also, one rib was tested to destruction by the application of external loads through the fittings and then cut into physical properties specimens.

Subsequent to the above program, new material with higher physical properties became available. As a consequence, two ribs (No. 4 and 5) were fabricated with Narmco 5206 system by Monsanto. One rib was destructively tested and then cut up to make physical property test specimens. The results of the structural properties tests conducted on QC tabs from ribs No. 0 through 5 are shown in Table 1.

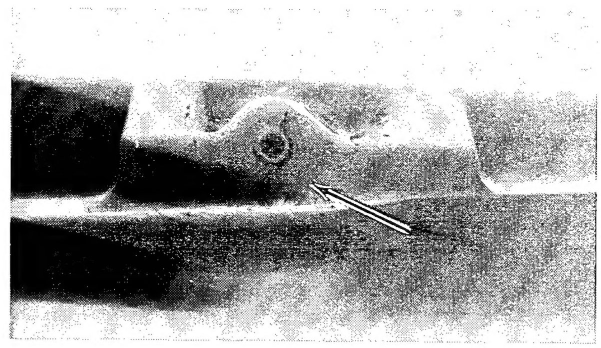
TABLE I
RESULTS OF STRUCTURAL PROPERTIES TESTS CONDUCTED ON THE RIB QUALITY CONTROL TABS

RIB NO.	WEIGHT (% RESIN CONTENT*)	VOLUME (% VOID CONTENT*)	HORIZONTAL SHEAR ULTIMATE (PSI)*	EDGEWISE SHEAR ULTIMATE (PSI)**	FLEXURAL STRENGTH (PSI)***	FLEXURAL MODULUS (PSI)***
0	43.88	2.06	6,547	16,440	83,400	14,624,000
1	47.73	2.41	7,306	15,300	47,300	13,235,000
2	50.95	1.69	7,948	18,400	57,160	11,609,000
3	48.34	1.70	6,350	19,740	54,290	11,920,000
4	35.97	0.16	14,253	VOID TEST	170,450	17,990,000
5	33.95	0.62	12,700	TEST IN PROGRESS	163,460	18,200,000

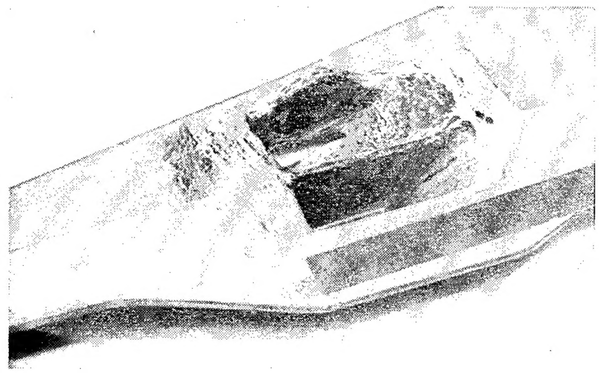
NOTES :
* AVE OF 4 VALUES
** AVE OF 3 VALUES
*** AVE OF 2 VALUES
RIBS NO. 4 AND 5 FABRICATED WITH NARMCO 5206 SYSTEM (MODMOR TYPE II) BY MONSANTO
RIBS NO. 0 THRU 3 FABRICATED WITH BP-907 RESIN/THORNEL 50 (MONSANTO) BY MONSANTO

All the ribs manufactured, including the initial effort rib No. 0 (made only as a mold checkout), were subjected to the same nondestructive examinations. The ribs were visually inspected for surface irregularities such as delamination, wrinkles, kinks, ridges, pits, bumps, etc. Water washable dye penetrant was used to enhance visual inspection. Fine cracks and surface porosity can be detected as shown in Figure 16. Radiographic inspection was used to detect cracks, inclusions, voids, fiber orientation, and porosity. Examples of some discontinuities are illustrated in Figures 17 and 18. Ultrasonic pulse-echo (reflector plate) inspection with C-scan data presentation was used to detect separations, voids, delaminations, and microporosity. The reflected sound beam is converted to electrical pulses, amplified, and displayed on a cathode-ray tube. The C-scan is a data presentation method that yields a two-dimensional view of the specimen. Through the use of a facsimile paper recorder a permanent record is obtained. Each rib was scanned in three segments because of the Z-shape geometry of the part. The results of this inspection on ribs No. 2 and 5 are shown in Figures 19 and 20. The inspection was performed with the use of a 5-MHz, medium-focused, searching unit. The light areas in rib No. 5 were caused by microporosity which is also evident in the radiographic reproduction (Figure 18).

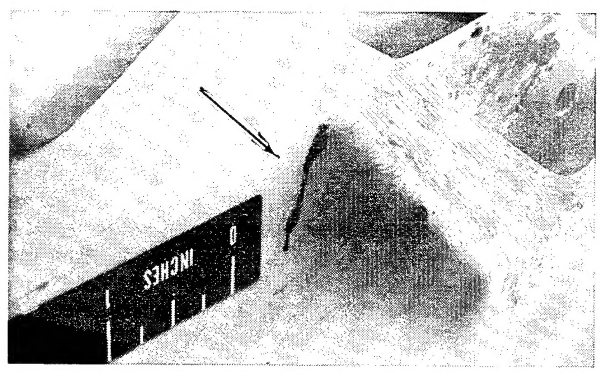
The results of the structural property tests on ribs No. 1, 2, and 3 showed no discernible differences in quality. The average interlaminar shear strength of the specimens increased with an increase in resin content. The flexural modulus decreased with an increase in resin content. The void content of all specimens tended to be in the same range: 1.7 to 2.4 percent. The void content did not appear to have any relation to the erratic strength values. The conclusions drawn indicated a minimum quantitative relationship exists between the results of tests conducted on the QC tabs and the results of tests conducted on similar specimens cut from adjacent areas in the rib. Certain



CRACK INDICATION RIB NO. 3

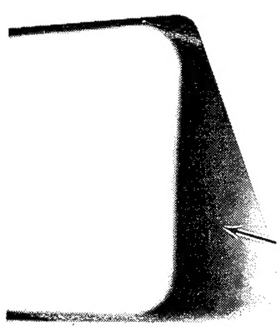


POROSITY RIB NO. 5

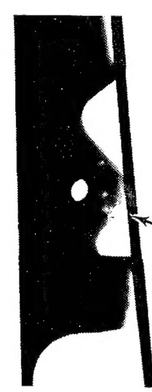


CRACK INDICATION RIB NO. 2

FIGURE 16. DYE PENETRANT INDICATIONS ON MOLDED GRAPHITE-EPOXY FLAP RIBS



INTERNAL SEPARATION OR CRACK RIB NO. 1



POROSITY AND VOIDS RIB NO. 1

FIGURE 17. RADIOGRAPHIC POSITIVE PRINTS OF MOLDED GRAPHITE-EPOXY RIB SHOWING INTERNAL DISCONTINUITIES

types of flaws: (1) kinks in yarns, (2) cracks, (3) misorientation of plies, and (4) areas of high porosity, all of which have an effect on the part strength, can be detected by NDT techniques. A recommendation was made to change the material to the high-strength Narmco 5206 graphite system; this was completed for ribs No. 4 and 5. The marked increase in properties is illustrated in Table I.

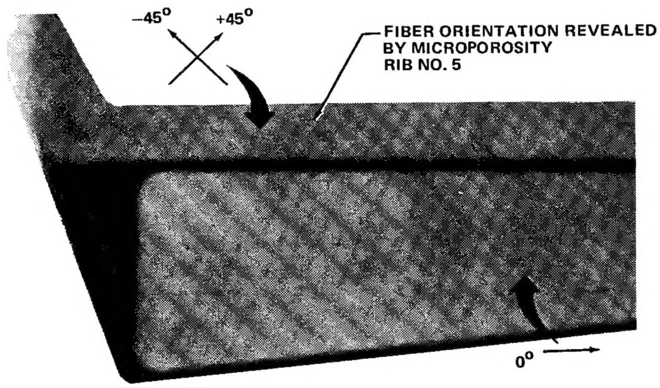


FIGURE 18. RADIOGRAPHIC POSITIVE PRINT OF MOLDED GRAPHITE-EPOXY RIB SHOWING INTERNAL DISCONTINUITIES

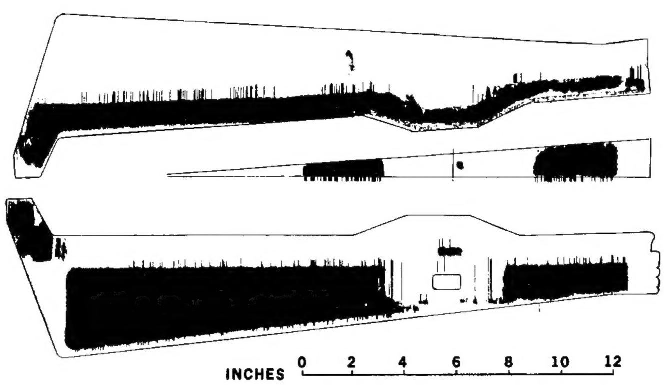


FIGURE 19. ULTRASONIC C-SCAN OF MOLDED GRAPHITE-EPOXY FLAP RIB NO. 2

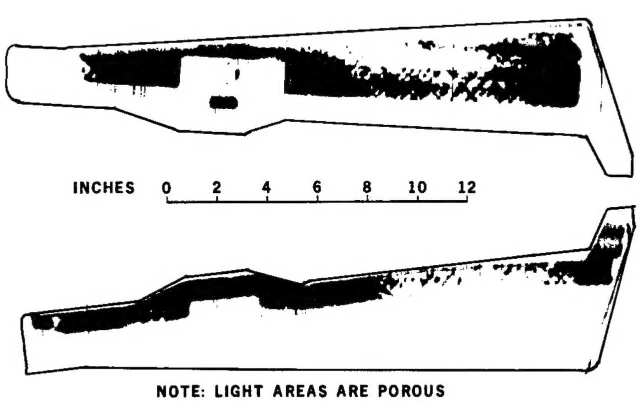


FIGURE 20. ULTRASONIC C-SCAN OF MOLDED GRAPHITE-EPOXY FLAP RIB NO. 5

ACOUSTIC EMISSION TESTS

A feasibility study was conducted to demonstrate acoustic emission test equipment for evaluating failure mechanisms in graphite composite tensile specimens. Tests were conducted on four ±45-degree and four unidirectional (fiber orientation) specimens. The acoustic emissions (stress waves) produced as the specimens cracked were detected, amplified, time integrated, and recorded. The recorded results varied slightly for each specimen tested but were basically identical for the two fiber orientation categories. Application of acoustic emission for nondestructive test evaluation is not yet a routine method. The purpose of the tests was to evaluate the equipment for application in research and development programs for composite materials.

The pressure waves produced in materials by the energy released as the material deforms and fractures are described as "acoustic emission." With adequate sensors and signal amplification, these pressure or stress waves can be detected at the material surface. This forms the basis for adapting this phenomenon to NDT.

EXPERIMENTAL PROCEDURE AND RESULTS

A PZT (lead zirconate titinate) transducer resonant at 150 kHz was taped to the side of the specimen and coupled with a viscous resin. The output of the transducer was amplified and passed through a bandpass filter set to pass frequencies between 120 and 170 kHz. The signals were then fed into a digital counter set to sum all signals counted (accumulation mode). The analog of this accumulated digital data was obtained from a digital-to-analog converter and displayed on the Y-axis of an X-Y plotter. The Dunegan Research Co. acoustic emission equipment is shown in Figure 21. The Bolt Beranek and Newman X-Y plotter is shown in Figure 22. The attachment of the transducer to a typical test specimen and the Instron tensile machine is shown in Figure 23.

The test specimen was mounted in the tensile machine and the transducer attached. The ±45-degree specimens were tested with a 1000-lb load cell. All the specimens were 1.0 inch wide by 0.0235 to 0.0250 inch thick. Specimen No. 1 was tested at a crosshead feed of 0.050 inch per minute with a 500-lb load cell. The grips slipped on the specimen. The load was increased to 1000 lb and the crosshead feed reduced to 0.025 inch per minute.

The results obtained from the eight test specimens are shown in Table II.

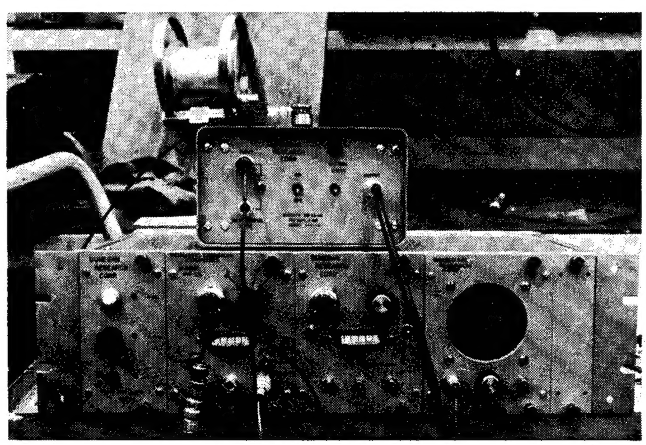


FIGURE 21. DUNEGAN RESEARCH COMPANY ACOUSTIC EMISSION INSTRUMENTATION

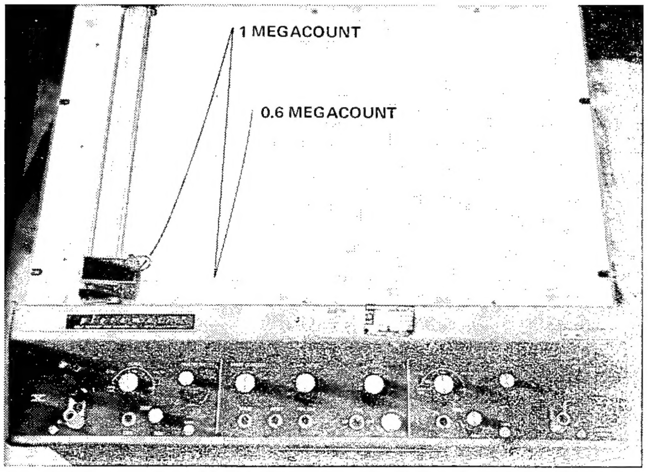


FIGURE 22. BOLT BERANEK AND NEWMAN X-Y PLOTTER

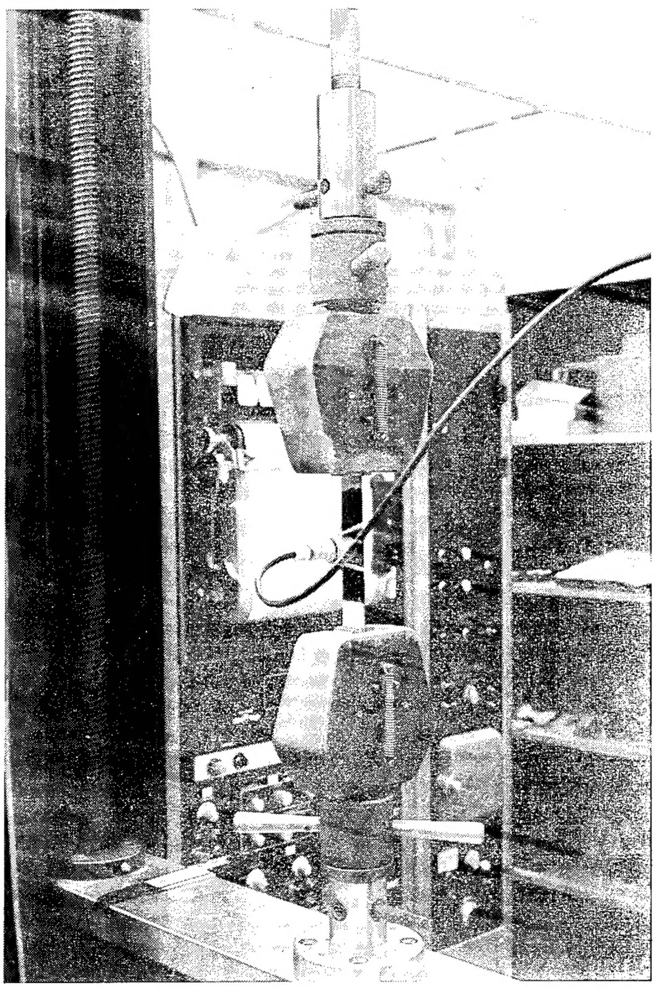


FIGURE 23. ATTACHMENT OF TRANSDUCER TO TYPICAL TEST SPECIMEN AND INSTRON TEST MACHINE

Specimens No. 1 through 4 broke in the center of the specimen at ±45 degrees. Specimens No. 5, 6, and 8 broke at the metal-bonded grip tabs, whereas specimen No. 7 broke near the middle of the specimen.

The relationship between total acoustic emission counts at failure versus load at failure is illustrated in Figure 24. It is obvious that the ±45-degree specimens yielded considerably more emissions

TABLE II
ACOUSTIC EMISSION TEST RESULTS

SPECIMEN NO.	WIDTH (IN.)	THICKNESS (IN.)	FIBER ORIENTATION	ULTIMATE LOAD (LB)	TOTAL DEFLECTION (IN.)
1	1.00	0.0235	± 45 DEG	550	
2	1.00	0.0240	± 45 DEG	554	0.1600
3	1.00	0.0250	± 45 DEG	528	0.1310
4	1.00	0.0248	± 45 DEG	510	0.1125
5	1.00	0.0244	UNIDIRECTIONAL	1750	0.0925
6	1.00	0.0243	UNIDIRECTIONAL	1875	0.0950
7	1.00	0.0245	UNIDIRECTIONAL	1575	0.0825
8	1.00	0.0245	UNIDIRECTIONAL	1400	0.0750

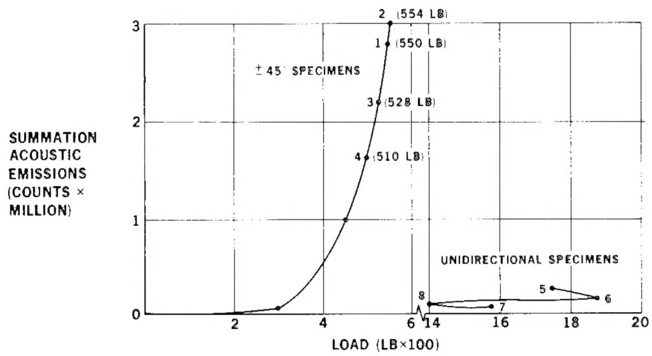


FIGURE 24. RELATIONSHIP BETWEEN FAILURE LOAD AND TOTAL ACOUSTIC EMISSION COUNTS

than did the unidirectional specimens prior to failure. Emissions started at 300-lb load for the ±45-degree specimens and reached 1 megacount at the 500-lb load. The specimens failed between 510 and 554 lb, yielding a linear acoustic count increase (at failure) between 1.5 and 3.0 megacounts. The 90-degree specimens failed at higher loads of 1400 to 1875 lb but the acoustic emissions ranged from 0.5 to 2.5 kilocounts at failure. Emission started at about a 1000-lb load for the 90-degree specimens versus a 300-lb load for the ±45-degree specimens.

To evaluate the amplitude of the signals would require the use of a high-speed video tape recorder and pulse-height analyzer. By playing back the tape, it might be possible to determine the difference in emission amplitude between matrix and fiber cracking. However, the results obtained in these tests most likely indicate high-amplitude signals caused by fiber cracking. In previous tests (Reference 1) using the Nortec equipment, it was possible to observe both the change in rate and amplitude while applying or holding the load constant. In the case of the quartz-phenolic tensile bars (Reference 1), signals of both high and low amplitude were observed while holding the load at 1500 lb, which indicated both fiber and resin cracking. The emission in the quartz-phenolic specimens began at a 400-lb load.

DISCUSSION

Previous investigations (References 1, 2, and 3) have shown that acoustic emission from metals is associated with the plastic deformation process. Tensile specimens without flaws have been observed to be very quiet until shortly before yielding occurs. Acoustic emission is high during and shortly after yielding, then decreases as further straining takes place. These findings indicate that if a structure or specimen is acoustically monitored during

loading, and emission is observed prior to general yielding, then there must be a stress concentration that is raising the stress level above the yield point concentration, and the presence of cracks would result in emission below the general yield point.

The beginning of acoustic emission is associated with the onset of plastic deformation in individual grains in a polycrystalline material and the acoustic emission reaches a peak in activity somewhere within the plastic region (Reference 3). The value of the plastic strain at this point of peak activity is different for each material. Since plastic deformation is an irreversible process, no acoustic emission is observed on a specimen that is recycled until the stress in the previous cycle has been reached or exceeded.

THERMAL OR INFRARED TESTS

The use of an ultraviolet transmitting coating, containing a thermoluminescent phosphor that emits light under excitation by ultraviolet radiation, permits the direct visual detection of disbonds as dark regions in an otherwise bright (fluorescent) surface, as illustrated in Figure 25. An experimental coating solution containing thermally sensitive phosphors was evaluated as a NDT technique on boron-composite, aluminum honeycomb-core flaps (Reference 1). When warm air (150°F) from a heat gun was played across the surface of the coated flap, the resultant local temperature of the coating varied due to the heat sink effect of the honeycomb cell walls. This temperature variation was seen as bright lines that traced out the honeycomb and as dark areas in the middle of the cells, when viewed with ultraviolet light. Unbonded areas of a single cell wall were distinguishable with this technique.

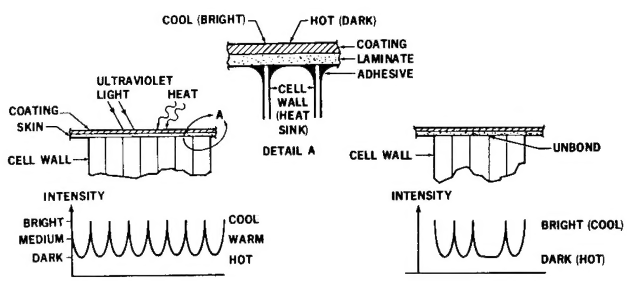


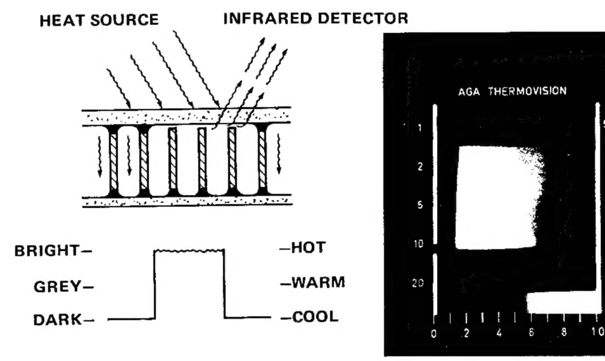
FIGURE 25. THERMOLUMINESCENT COATING TECHNIQUE ON GRAPHITE COMPOSITE/ALUMINUM HONEYCOMB ASSEMBLY

Feasibility studies were conducted, using the thermoluminescent coating on graphite-composite specimens. It was determined that thermal techniques were sensitive for detecting disbonds in thin graphite facing sheets to aluminum-core honeycomb assemblies typical to the A-4 flap. It did not detect disbonds in graphite-to-graphite joints or graphite skin to phenolic honeycomb core, both of which are being used in the A-4 horizontal stabilizer. These results were anticipated because of the poor thermal conductivity of graphite and back-up material which eliminates the thermal differential necessary for detection.

Quartz heating lamps and Detecto-Temp (thermochromic paint) have been ordered for use in future NDT evaluations on composite to metal bond joints. Detecto-Temp paints (Reference 4) are composed of a mixture of temperature-indicating materials with the capability to change color when certain temperatures are reached. There are 36 paints, covering temperature ranges from 104 to 2962°F. They are easy to apply and remove, and provide visible isothermal patterns over the surface of the test object. The color change is permanent except with seven of the paints. With these seven, the color change is a result of water vapor evaporation. As these paints cool, they slowly reabsorb moisture from the atmosphere and return to their original color. This may take hours or days, depending upon the humidity. For NDT evaluations, the 104°F (pink to blue) and 140°F (light green to blue) color-change paints have been used.

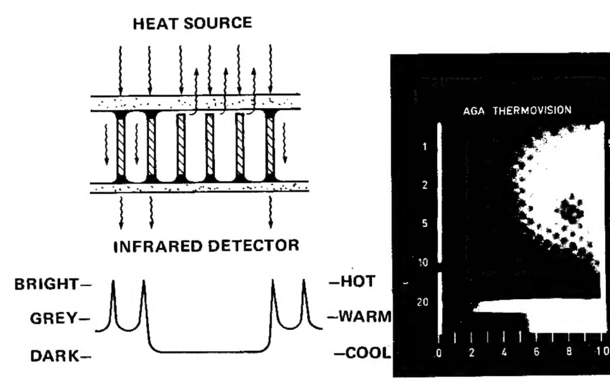
Many investigators have used cholesteric liquid crystals (References 5 and 6) or radiometers (Reference 7) for isothermal evaluations of bonded structures. However, the radiometer tests are surface emissivity dependent and false indications are sometimes obtained. The liquid crystals are expensive and the thermal pattern changes rapidly through many colors. Hence, the authors prefer to use the thermoluminescent or thermochromic paints for thermal or infrared NDT evaluations.

Figure 26 illustrates typical results for thermal testing of composites with the use of an infrared radiometer thermovision method. View A shows the results obtained with the radiometer scanning the heated surface of a graphite composite (HMG 50, 12 ply, ±45 degrees) aluminum-core honeycomb composite. The bright spot is caused by a 1/2-inch-diameter disbond located on the heated side of the specimen. View B shows the results obtained by heating one side and observing the opposite side of



VIEW A

OBSERVING HEATED SIDE OF GRAPHITE-FIBER COMPOSITE, ALUMINUM-CORE HONEYCOMB



VIEW B

OBSERVING UNHEATED SIDE OF GRAPHITE-FIBER COMPOSITE, ALUMINUM-CORE HONEYCOMB

FIGURE 26. INFRARED RADIOMETER METHOD OF FOR INSPECTING COMPOSITES

the specimen. The small grey spots are the natural honeycomb cells; the two larger dark spots are 3/4- and 1/2-inch-diameter disbonds located on the heated side of the specimen. These tests were easily conducted with the use of the AGA thermovision instrument. Unfortunately, the instrumentation is quite costly and purchase could not be justified for low-budget research programs.

In conclusion, there are three conditions that limit the sensitivity of infrared or thermal tests and, consequently, their usefulness for void inspection: (1) surface emissivity, (2) coefficient of thermal conductivity of facing sheet or laminate, and (3) thickness of the facing sheet or laminate. Also, controlled heating must be used because of the time/temperature dependence for repeatable test results.

CONCLUSIONS

Regarding the NDT evaluation of graphite-composite structures as indicated by results of the tests reported herein, the following conclusions are drawn:

1. Liquid penetrants are useful for detecting surface cracks and porosity.

2. X-ray radiography is useful for detecting cracks, voids, inclusions, fiber orientation, porosity, internal assembly fit-up, and crushed or wrinkled honeycomb core.

3. Ultrasonic C-scan yields a two-dimensional view of the specimen which is useful for detecting cracks, voids, porosity, lack of bond, and fiber orientation.

4. Sonic test methods, i.e., Harmonic Bond tester, Fokker, etc., are useful for detecting large voids, crushed core, and lack of bond.

5. Acoustic emission shows promise as a tool for micromechanic studies of filament cracking or filament/matrix separation during tensile or fatigue testing.

6. Thermal or infrared test methods are useful for detecting lack of bond in thin facing sheet to metal backing bonded structures. This is especially useful when the part or assembly cannot be immersed in water for ultrasonic C-scan inspection, and also useful where part geometry makes ultrasonic inspection difficult to perform.

7. In addition to NDT, other in-process quality control tests are required. Generally, oversize panels are made with provisions for removing coupons for mechanical properties along with resin and void content measurement. Selection of test specimen location can be determined by material variability as revealed by NDT methods.

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